Energy Storage and Conversion 2025, 3(1), 1959.
https://doi.org/10.59400/esc1959

Perspective

Enhancing the performance and durability of high-temperature heat transfer fluids in industrial applications: A short review

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CITATION

Wright CI. Enhancing the performance and durability of high-temperature heat transfer fluids in industrial applications: A short review. Energy Storage and Conversion. 2025; 3(1): 1959. https://doi.org/10.59400/esc1959

ARTICLE INFO

Received: 3 February 2025
Accepted: 20 March 2025
Available online: 10 March 2025

Abstract: This article discusses typical heat transfer fluids (HTFs), crucial for efficient heat transfer in various industrial processes. HTFs play an important role circulating heat within closed-system operations, such as chemical processing, and also in storing and transferring thermal energy, for example, in concentrated solar power plants. Selecting the right HTF is key, as it must be compatible with the specific temperature range of the operation, thermally stable at high temperatures, and compatible with system materials. Safety is also a crucial factor, both in terms of personal safety during handling of the fluid and environmental impact of fluids. Regular monitoring is also a key consideration when selecting and using a fluid. as the condition of the HTF and system are interlinked. Regular sampling and monitoring of the fluid's condition helps to identify potential issues like oxidation, contamination, and thermal decomposition, and thus helps to prevent or slow degradation while sustaining optimal performance. Strategies for extending the lifespan of a HTF include routine monitoring and the utilisation of other technologies, as needed, to protect against oxidation (e.g., anti-oxidative additive packages) and volatile light-ends (e.g., installation of a light-ends removal kit). By adopting such measures, industries can reduce operating costs, minimize downtime, and improve overall system efficiency. The objective of this short review is to provide a brief overview of the main HTFs used in high temperature industries and offer insights into the importance of selecting the right HTF for a specific application, considering factors such as its thermal properties, chemical stability, and safety. The need for regular monitoring and maintenance is emphasized to ensure optimal performance and extend the lifespan of HTFs.

Keywords: heat transfer fluid; thermal fluid; thermal stability; fluid degradation; system efficiency; fluid monitoring; personal safety; environmental safety; industrial applications

1. Introduction

Heat Transfer Fluids (HTFs) are essential for maintaining stable temperatures in various industrial processes, from food processing to power generation from renewable energy and energy storage [1]. They circulate heat within closed systems, enabling efficient energy transfer, and their performance plays a crucial role in the efficiency and reliability of industrial operations. HTFs are commonly grouped according to their properties (e.g., organic HTFs, synthetic HTFs) and support operations requiring high temperatures, such concentrated solar power plants. These systems utilise technologies like parabolic trough collectors, concentrating linear Fresnel reflectors, or solar power towers to heat a HTF to working temperatures between 288 °C and 549 °C (550 °F and 1020 °F) [2]. With the move to more sustainable practices, there is a growing need for advanced HTFs to operate at elevated temperatures and to maintain chemical stability and excellent thermal capabilities. Indeed, a well-designed high-temperature HTF should provide a wide operating temperature range but also a low minimum temperature to maintain good fluidity and pump protection in colder environments. Both of these features are crucial to avoid premature degradation of the fluid. The current article discusses the key features that are essential to the operation of a HTF and offers insights into the choice of HTF, specifically focusing on organic and synthetic HTFs.

The management of HTFs is another critical aspect, and regular monitoring of a HTF's condition is central to operations. This proactive approach helps prevent fluid degradation and optimise its performance. Routine sampling and laboratory analysis allows manufacturers to identify potential issues, such as oxidation and contamination, and to make informed decisions about interventions and corrective actions to extend the lifespan of a fluid. There are several approaches that can be utilised, for example the use of additives to enhance thermal stability and resist oxidation, the installation of light-ends removal kits to manage and remove volatile compounds generated during fluid degradation. These approaches can be employed to reduce operating costs, minimise downtime, and improve the overall efficiency of both the fluid and the entire system.

This short review article is organised into key areas and includes sections on the types of HTF, how to choose the right HTF, monitoring thermal degradation, and technologies to extend the lifespan of a fluid.

2. Heat transfer fluids

HTFs can be classified into six main categories based on their material properties: (1) gaseous HTFs, such as air, (2) aqueous HTFs, including water and steam, (3) organic-based fluids (e.g., Castrol Perfecto HT 5 (red), Globaltherm M) and highly refined organic fluids (e.g., Globaltherm FG), (4) synthetic fluids (e.g., Dowtherm A), (5) molten salts, and (6) liquid metals [3]. These fluids offer a solution for heating processes that require temperatures exceeding the practical limits of steam heating. By utilising a fired heater or furnace as a heat source, HTF systems can routinely achieve operating temperatures up to 400 °C, depending on the specific HTF that is used [1,3]. Traditional processes, heavily reliant on steam-based systems, often struggle to achieve the high temperatures required for certain reactions [4]. As industries transition towards electrification and decarbonization, there is a growing need for alternative HTFs that can operate at elevated temperatures (i.e., ≥400 ℃ [≥752 °F]) while maintaining exceptional thermal and chemical stability, and ensuring efficient heat transfer at ambient pressure [4]. Heller [5] presented nine important thermophysical properties of a HTF, including low solidification temperature for fluidity at low temperatures, a high upper temperature limit for high-temperature operation, high thermal conductivity for efficient heat transfer, low viscosity for reduced pumping power requirements, high density and heat capacity for energy storage, the potential to be used as a working fluid, chemical compatibility with system materials to minimise corrosion, low cost and high availability, and low toxicity and environmental impact.

2.1. Water/steam HTF

This is considered feasible for low- to medium-temperature systems and fulfils a number of the desirable characteristics of a HTF previously mentioned. However, the freezing and boiling points of water mean it has a relatively narrow temperature range for use as a HTF [6].

Compared with synthetic HTFs and molten salts, its thermal conduction performance and heat storage capacity are lower [7]. Organic and synthetic HTFs are viable alternatives to water/steam and the preferred choice at temperatures above 200 ℃ (392 °F) [8]. They are also used in operations at significantly lower pressures, providing a significant advantage compared to traditional mediums like steam [9]. For example, at 343 ℃ (650 °F), water/steam exerts a pressure of 13,789.51 kPa (2000 psi), while synthetic fluids (e.g., Therminol 66, Globaltherm Syntec) operate at much lower pressures, typically between 71.02 and 86.18 kPa (10.3 and 12.5 psi) [10]. This lower pressure offers a few distinct advantages, including reduced equipment costs and increased safety. Another advantage is the lower freezing point compared to water. For example, Globaltherm Syntec has a pour point of roughly −28 ℃ (−18.4 °F) [11] versus 0 ℃ (32 °F) for water, generally making synthetic fluids more suitable for applications in colder climates [9].

2.2. Organic and synthetic HTFs

Based on chemical composition, fluids are classed as mineral or synthetic [1]. Organic HTFs, obtained through the fractional distillation of heavy oil, are composed of naphthenic and paraffinic compounds. The long, straight-chain structures of these compounds make them prone to thermal cracking, which can limit their thermal stability below roughly 300 ℃ (572 °F).

Organic HTFs, derived from mineral oil, are complex mixtures of petroleum distillates obtained from crude oil refining processes [1]. The optimal operating temperature for an HTF is determined by its base chemistry and purity [9]. As a general rule, organic HTFs are considered a cost-effective solution for applications requiring high-temperature performance and moderate thermal stability.

Synthetic HTFs are specially engineered fluids produced through chemical synthesis [9]. They primarily consist of symmetric alkyl aromatic compounds containing benzene rings, and are manufactured through a rigorous process involving synthesis, separation, and purification of chemical raw materials. These fluids exhibit high initial boiling points, narrow distillation ranges, and fully conjugated molecular structures, contributing to their enhanced stability, thermal conductivity, lower viscosity, and higher enthalpy [1].

Synthetic fluids are designed to offer long-lasting, efficient performance and are resistant to chemical degradation during prolonged operation at high temperature [1]. Based on their purer chemical composition, they tend to have better thermal stability than organic HTFs and also have a lower propensity to foul thermal systems, resulting in cleaner operating systems.

Compared to molten salts, synthetic fluids tend to be less corrosive, making them widely compatible with various materials and suitable for use in a wide range of applications. These fluids are considered economical and also practical, as they pose a relatively minimal risk of fire or explosion when used correctly and managed properly [1,7].

The selection of any fluid involves a trade-off as not all fluids are the same. Indeed, biphenyl-diphenyl oxide-based HTFs generally operate at higher temperatures compared to terphenyl-based HTFs. However, this higher operating temperature comes at the cost of a higher freezing point, limiting their suitability for applications in colder climates [9].

Compared to water, these fluids exhibit reduced reactivity and corrosiveness, leading to increased durability and reduced system degradation. They are also recognised for their relatively good safety profile, low cost, and low toxicity. Some disadvantages include their performance at low temperature, where their viscosity can increase (e.g., in the case of terphenyl-based HTFs), potentially leading to pipeline blockages and oil degradation. **Table 1** provides a short list of some common organic- and synthetic-based HTFs for comparison.

Table 1. Typical temperature characteristics for organic and synthetic heat transfer fluids.

Manufacturer	**Specification**	**Fluid type**	**Operating range °C (°F)**	**Flash point temperature, open cup, °C (°F)**	**Density, kg/m^3**	**Specific heat capacity, kJ/kg*K**	**Kinematic viscosity, mm^2/s**	**Thermal conductivity, W/m*K**	**Reference**
Global Heat Transfer	Globaltherm M	Organic	−10 to 320 (14 to 608)	230 (446)	873 (at 25 °C / 77 °F)	Not reported	29.8 at 40 °C (104 °F) 4.5 at 100 °C (212 °F)	Not reported	[12]
Mobil Oil Corporation	Mobiltherm 605	Organic	−12 to 315 (closed system) (10.4 to 599)	230 (446)	857 (at 15 °C / 59 °F)	Not reported	30.4 at 40 °C (104 °F) 5.4 at 100 °C (212 °F)	Not reported	[13,14]
Shell Oil Company	Shell Heat Transfer Oil S (previous name, Shell Themia B)	Organic	−12 to 320 (10.4 to 608)	220 (428)	857 (at 20 °C / 68 °F)	1.809 at 0 °C (32 °F) 3.048 at 340 °C (644 °F)	29 at 40 °C (104 °F) 5.1 at 100 °C (212 °F)	0.136 at 0 °C (32 °F) 0.118 at 250 °C (482 °F)	[15,16]
Castrol	Perfecto HT 5 (red) (previously called Transcal N (red))	Organic	−10 to 320 (14 to 608)	221 (429.8)	875 (at 15 °C / 59 °F)	Not reported	31 at 40 °C (104 °F) 5.2 at 100 °C (212 °F)	0.129 at 0 Not reported	[17]
Global Heat Transfer	Globaltherm Omnitech	Synthetic (Biphenyl (C12H22), diphenyl ether (C12H10O))	15 to 400 (59 to 752)	123 (253.4)	1056 (at 25 °C / 77 °F)	Not reported	2.5 at 40 °C (104 °F) 0.97 at 100 °C (212 °F)	Not reported	[18]
Dow Chemical Company	Dowtherm A	Synthetic (Biphenyl (C12H22), diphenyl ether (C12H10O))	15 to 400 (59 to 752)	113 (235.4) [d]	1063.5 (at 15 °C / 59 °F)[a]	1.558 at 15°C / 59 °F 2.725 at 405°C (761 °F)[a]	5.0 at 15°C (59 °F) 0.91 (at 105 °C (221 °F) Note: 0.12 at 405 °C (761 °F) [a,b,c]	1.395 at 15 °C / 59 °F 0.0771 (at 405 °C (761 °F) [a]	[19]

Table 1. (*Continued*).

Manufacturer	**Specification**	**Fluid type**	**Operating range °C (°F)**	**Flash point temperature, open cup, °C (°F)**	**Density, kg/m^3**	**Specific heat capacity, kJ/kg*K**	**Kinematic viscosity, mm^2/s**	**Thermal conductivity, W/m*K**	**Reference**
Solutia	Therminol VP-1	Synthetic (Hydrogenated terphenyl ($C_{18}H_{22}$))	12 to 400 (53.6 to 752)	124 (255)	1068 (at 15 °C / 59 °F)	1.523 at 12 °C / 53.6 °F 2.729 at 420 °C (788 °F)[a]	2.48 at 40 °C (104 °F) 0.986 at 100 °C (212 °F) Note: 0.206 at 420^{0}C (788 °F) [a,c]	0.1370 at 12 °C / 54 °F 0.0710 (at 420 °C (788 °F)[a]	[20,21]
Eastman	Marlotherm SH	Synthetic (Benzyl toluene ($C_{14}H_{14}$))	−5 to 350 (23 to 662)	219 (426)	1045 (at 15 °C / 59 °F)	1.49 at 0 °C / 32 °F 2.82 at 360 °C (680 °F)	16.4 at 40 °C (104 °F) 3.18 at 100 °C (212 °F) Note: 0.326 at 360 °C (680 °F)	0.1331 at 0 °C / 32 °F 0.0856 (at 360 °C (680 °F)	[22]
Wacker	Helisol 5A	Synthetic (Polydimethyl Siloxane)	−5 to 430 (23 to 806)	120 (248) [d]	920 (at 25 °C / 77 °F)	1.435 at 0 °C / 32 °F 2.005 at 250 °C (482 °F)	4.16 at 40 °C (104 °F) 1.89 at 100 °C (212 °F) Note: 0.59 at 250 °C (482 °F)	0.1349 at 0 °C / 32^{0}F 0.0806 (at 250 °C (482 °F)	[23,24]
TotalEnergies Lubricants	Jarytherm BT 06	Synthetic (Blend of benzyl-($C_{14}H_{14}$) and dibenzyltoluene isomers. ($C_{21}H_{22}$))	−65 to 290 and 350 under pressure (-85 to 554 and 662)	140 (284)	943 (at 15 °C / 59 °F)	1.609 at 20 °C / 68 °F 2.493(at 300 °C (572 °F)	3.32 at 40 °C (104^{0}F) 1.33 at 100 °C (212^{0}F) Note: 0.39 at 300 °C (572 °F)	0.142 at 20 °C / 68 °F 0.115 (at 300 °C (572 °F)	[25]

Notes: The reported typical values for a fluid can change due to continual product research and development, and readers should consult the latest versions available. [a]Saturated liquid properties. [b]Dynamic viscosity in mPa ● s. [c]1 cSt = 1 mm^2/s and 1 mPa ● s = 1 cP. [d]Closed flash point temperature.

Synthetic HTFs are used in commercial parabolic trough CSP plants [26]. Common synthetic HTFs include eutectic mixtures of biphenyl and diphenyl oxide such as Therminol VP-1, Dowtherm A, and Globaltherm Omnitech [18–20], which have an upper operating temperature of approximately 400 °C (752 °F). As previously mentioned, these HTFs tend to have strong fluid performance, a low freezing point, fluid depending, low corrosivity and good heat transfer performance [7]. However, they present several disadvantages. For instance, they will degrade over time and are considered flammable [7]. Thermal degradation is discussed in more detail later in this article.

2.3. Nanofluids

Numerous ongoing studies are investigating the use of nanoparticles or hybrid (two or more different types of nanoparticles [27]) in base to enhance fluid thermal performance. A nanofluid is defined as an engineered colloidal suspension of nanoparticles suspended in a base fluid, such as an organic HTF. These fluids typically contain nanoparticles ranging in size from 10 to 100 nm, constituting 0.01 to 5.0% of the fluid by weight. Examples include metals, metal and non-metal (copper oxide (CuO), zinc oxide (ZnO), titanium dioxide (TiO_2), silicon dioxide/silica (SiO_2)), carbides, and carbon materials [7].

Nanoparticles have potential applications in various engineering fields, including heat exchangers, electronic cooling, and solar energy systems [27], which has been extensively researched over the last decades.

The impact of copper oxide CuO nanoflakes on the thermal conductivity of mineral oil has been investigated by Abutaleb and Imran [28]. At a concentration of 0.46% volume, thermal conductivity was increased by 15.73%, and is considered of potential relevance to minimising the effects of heat in electronical devices and computers.

In the context of CSP, Zhang et al. [29] demonstrated that the convection heat transfer coefficient of a quaternary molten salt (containing four different salt components) increased by 22.34% when incorporating SiO2 nanoparticles. Simulations and experiments have also shown silica nanoparticles can enhance the specific heat capacity of molten salts composed of sodium nitrate, potassium nitrate and lithium nitrate [30].

Recent CSP research has focused on enhancing thermal properties, expanding operating temperature ranges, and optimising the rheological behaviour of fluids, as outlined by Wang et al. [7]. However, the large-scale production of nanofluids for CSP remains an ongoing area of research.

2.4. Molten salts

Inorganic molten salts exhibit several desirable properties that make them suitable HTFs for high-temperature applications. These properties include high thermal stability, high specific heat capacity, high convective heat transfer coefficients, low viscosity, and low vapour pressure. Based on their chemical composition, molten salts can be classified into five main categories: nitrates, carbonates, chlorides, fluorides, and sulphates. **Table 2** provides a comprehensive overview of the melting and boiling temperatures of various molten salts.

Table 2. Melting and boiling temperatures of different molten salts.

Molten salt	Melting temperature ℃ (°F)	Boiling temperature ℃ (°F)
Sodium nitrate ($NaNO_3$)	310 (590)	[a]380 (716)
Sodium nitrite ($NaNO_2$)	270 (518)	[a]320 (608)
Potassium nitrate (KNO_3)	537 (998.6)	537 (998.6)
Sodium carbonate (Na_2CO_3)	851 (1563.8)	1600 (2912)
Potassium carbonate (K_2CO_3)	891 (1635.8)	[a]1310 (2390)
Lithium carbonate (Li_2CO_3)	723 (1333.4)	1342 (2447.6)
Sodium chloride (NaCl)	801 (1473.8)	1465 (2669)
Potassium chloride (KCl)	770 (1418)	1420 (2588)
Magnesium chloride ($MgCl_2$)	714 (1317.2)	1412 (2573.6)
Potassium fluoride (KF)	858 (1576.4)	1502 (2735.6)

[a] Decomposes at this temperature. Table adapted from [7].

A major challenge associated with molten salt materials is their tendency to cause pipeline blockages due to their high melting points. Furthermore, some simple molten salts exhibit relatively low boiling points, making them susceptible to decomposition at elevated temperatures. For example, Solar Salt (60% $NaNO_3$ and 40% KNO_3) can withstand temperatures up to 600 ℃ (1112 °F), but a lower maximum operating temperature is typically selected to ensure acceptable corrosion rates with the chosen stainless steel [31]. One approach to addressing these limitations has been the development of multi-component molten salts or advanced salts with broader operating temperature ranges. However, simultaneous achievement of low melting points and high decomposition temperatures in multi-component salts remains an ongoing research objective at the present time [7]. In terms of advantages, molten salts exhibit high specific heat capacity, strong heat storage capacity, and the potential for direct storage at relatively low costs [5]. Further, molten salts offer advantages beyond high-temperature tolerance and thermal energy storage capabilities, as they are relatively more cost-effective compared to other HTF options [3]. Like organic and synthetic fluids, they can operate at low pressure, they have low flammability, a good safety profile, and are non-toxic [7].

2.5. Liquid metals

While molten salts have temperature limitations, other HTFs, like liquid metals and their alloys, offer a wider operating temperature range. These fluids can remain liquid at temperatures below 0 ℃ (32 °F) and can withstand temperatures exceeding 1600 ℃ (2912 °F) [5]. Liquid metals possess outstanding heat transfer characteristics and low viscosity, further enhancing their suitability as HTFs. They are currently being considered are potential alternatives to molten salts and synthetic HTFs for use in the next generation CSP systems [7].

3. Choosing the right heat transfer fluid

The selection of an inappropriate HTF can precipitate accelerated degradation, equipment malfunctions, fouling of system components, increase maintenance requirements, and diminish overall system efficiency. Conversely, well-designed and maintained heat transfer systems that utilise suitable HTFs are relatively safe when managed routinely and thus require minimal maintenance [6].

When selecting a HTF, one general piece of guidance for buyers is to thoroughly research the product before making a purchase. This includes liaising with the supplier to understand the fluid in detail, obtaining a copy of the safety data sheet, comparing the properties of different fluids, and evaluating its thermal stability, heat transfer rate, and fouling potential. The second piece of advice is to choose a well-designed and high quality fluid [9].

Figure 1 outlines the key features of a well-designed high-temperature HTF [6,9]. A key consideration is usually the operating range, which encompasses both the minimum and maximum operating temperatures. The minimum temperature concern is fluidity, ensuring the HTF remains sufficiently fluid for efficient heat transfer and that flow is not sluggish, potentially putting the pump at risk [32,33].

The maximum defines the limit for efficient performance and stability of the fluid. If the maximum temperature is exceeded, fluid degradation accelerates, which can lead to system problems [32,34]. There is also the minimum start-up temperature to consider, which is crucial in very cold environments. An HTF with a minimum start-up temperature above the ambient temperature can lead to operational challenges. Conversely, an HTF with a lower start-up temperature promotes longer fluid life and reduces the risk of premature degradation during start-up [35]. Other critical considerations include the potential for fouling due to the presence of impurities [9], the fluid's expansion rate and its impact on system sizing, as well as the flash and fire point temperatures [33,36], and resistance to oxidation [1]. Different chemistries exhibit varying levels of inherent oxidation resistance, and additives can be introduced to enhance this property. However, the potential impact of additives must be considered when assessing the overall capabilities of the fluid [6].

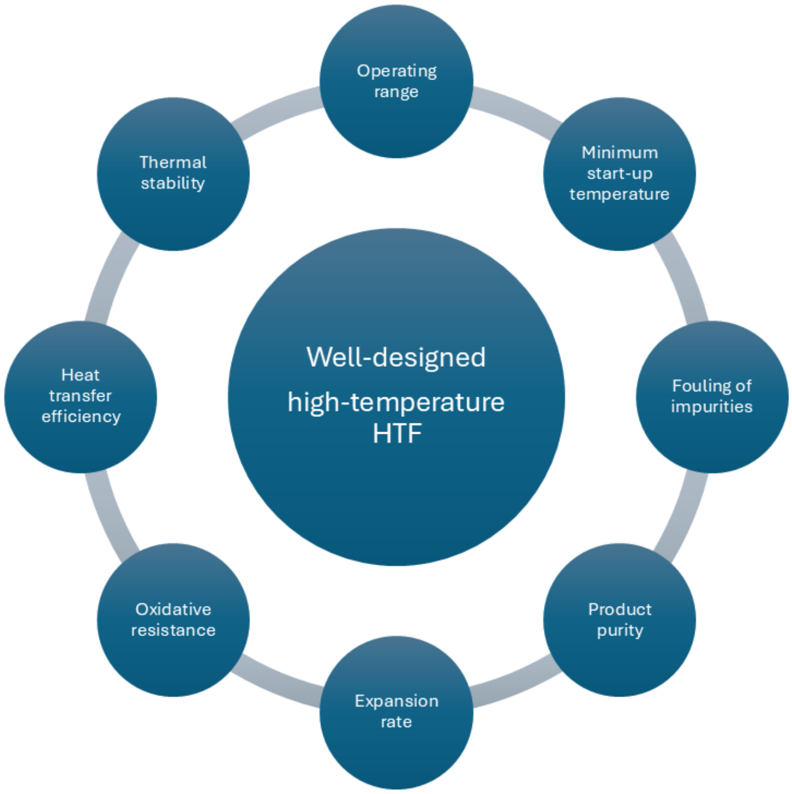

Figure 1. The key product features for a well-designed high-temperature heat transfer fluid [6,9].

4. Monitoring thermal degradation

4.1. Routine sampling

It is well-known that fluids will thermally degrade over time [1]. The two most common processes of degradation are thermal cracking and oxidative stress [36], with the formation of light and heavy hydrocarbons during thermal cracking and the formation of organic acids and sludge in the presence of oxygen [37]. Routine sampling and chemical analysis are important in the assessment of a fluid's health

[34]. A standard battery of tests for a HTF involves tests that assess the physical properties of the fluid and assess potential contamination.

It is generally well accepted that a HTF system needs to be sampled as frequently as is feasibly possible [34]. The general rule of thumb from HTF manufacturers is that fluids should be sampled and tested at least once per year if they operate at bulk temperature, more recent research based on organic HTFs suggests that more frequent sampling, such as every three months, can improve fluid condition. This research also indicated that carbon, neutralisation number and closed flash temperature are more likely to fall outside of specifications when systems are sampled less frequently, such as once every two to three years [34].

4.2. Safe sampling station

Before taking a sample, it is crucial to ensure the safety of the sampling area and that there is clear, unobstructed access to the sampling port [38]. Furthermore, the sampling port should be located below chest level to minimize the risk of upper body exposure to the HTF. Additionally, the design of the sampling area should minimise the reach required, thus avoiding physical strain. Sufficient space should be provided beneath the port for hands-free placement of a labelled flush bucket. Non-slip flooring is essential to prevent accidents, and globe valves are recommended for precise flow rate control to minimise spills and overfilling [39].

4.3. Gaining a representative sample

Safe sampling of HTFs at extreme temperatures is a fundamental part of the training for all engineers involved and obtaining a representative sample should only be conducted by experienced engineers [40].

Obtaining a representative HTF sample is important to being able to understand the health of the fluid and the system. Several important elements must be considered during the sampling process (please see **Figure 2**). Before taking a sample, it is advisable to review the safety data sheets for the fluid in question to understand its physical and chemical properties, and associated hazards. Engineers should familiarise themselves with the guidance on handling and personal protective equipment. This guidance often advises wearing gloves that provide chemical and thermal protection, along with safety goggles, a face mask, and a splash apron to protect against any potential sprays (see **Figure 3**).

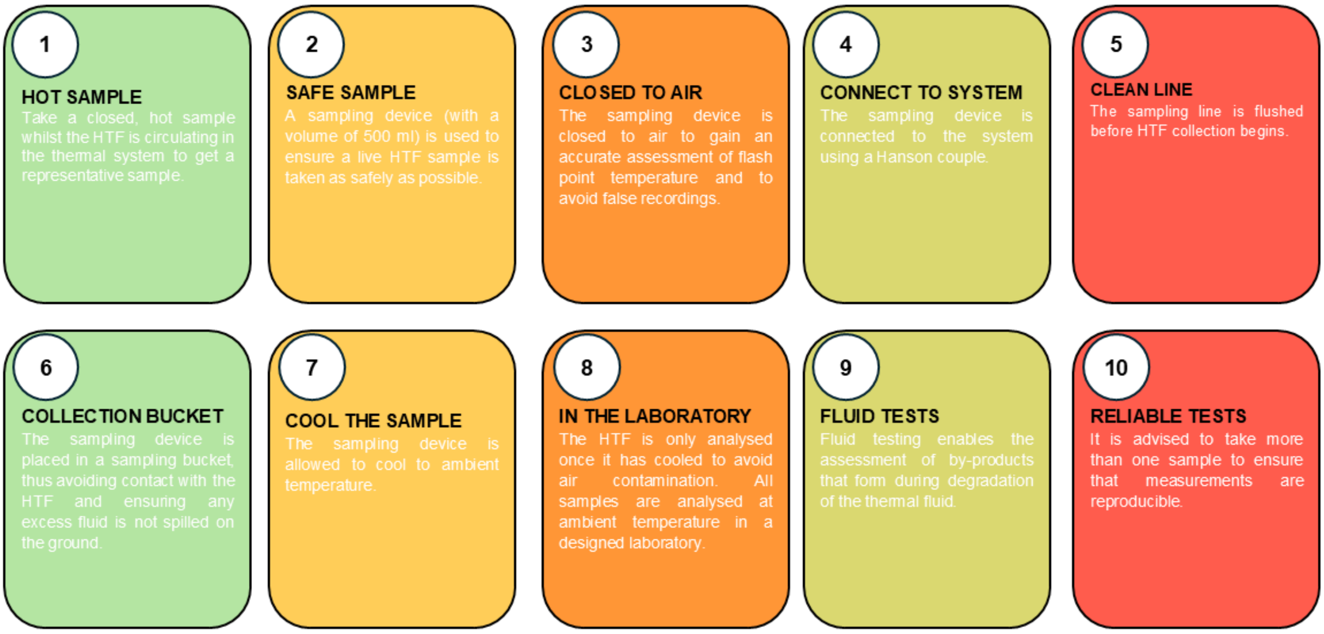

Figure 2. Considerations for gaining a true representative sample of the high-temperature heat transfer fluid [38].

	Health and safety risk	Actions to minimise identified risks
Ears	• Deafening noise from operating equipment.	• Wear ear defenders.
Eyes, face, skin	• Splashing of hot fluids and chemicals, as well as exposure to dust and gas.	• Wear safety spectacles, a facemask to protects the skin, coveralls / apron to protect the skin / the body.
Feet	• See 'Hands, wrist, arms.' The feet and legs need protection from safety risks such as hight temperature sprays, chemical splashes, and falling objects.	• Wear tight-fitting boots that provide some heat resistance and have a non-slip sole. They should have a steel toecap to protect the toes and penetration-resistant mid-soles. Open-topped footwear, such as rigger boots, must not be worn as high temperature fluids could penetrate these boots.
Hands, wrists, arms	• Hazards include abrasion, temperature extremes, cuts, contact, and contamination with chemicals.	• Wear heat-rated gauntlets / gloves that are non-porous and resistant to fluid penetration. A cotton inner glove is also recommended as this serves as an additional layer of protection and cotton helps to stop moisture pooling in the gauntlet.
Head	• Any form of head injury such as bumping stationary objects; hair entanglement; impact from falling or flying objects.	• Wear a hard hat.
Lungs	• Vapours from the heat transfer fluid.	• Wear a respirator (half or full-face).

Figure 3. Personal health and safety considerations when sampling a high-temperature heat transfer fluid [40].

Upon entering the sampling station, it is advised to inspect the port area for uninsulated contact points to avoid any potential hazards. When taking a representative sample, it is important to extract it while the thermal system is in operation [38]. A 500 mL sampling device is employed to collect a live HTF sample safely and accurately. The device hermetically sealed to prevent air contamination, which can lead to inaccurate flash point temperature readings. A Hanson coupling is used to connect the sampling device to the system, and the sampling line is flushed thoroughly before sample collection. The collected HTF is transferred to a sampling bucket to minimize contact with the environment and prevent spillage. The sample is then allowed to cool to ambient temperature to avoid air contamination and a cooler can be used to maintain the fluid temperature below 93 ℃ (200 °F) to safeguard the integrity of the sample. The engineer should be aware of any drips throughout the sample collection and they should not remove their personal protective equipment until the port and the sampling device are secured and considered safe [38].

4.4. Laboratory analysis

The sample is returned to the laboratory where the fluid is analysed in a controlled environment based on the fluid's thermophysical parameters and the client's pre-specified requirements. These analyses generally focus on quantifying the formation of by-products of thermal degradation, physical properties of the fluid, contamination, and system wear, with repeated tests taken to ensure reliable and reproducible results [39,40]

Some of the typical parameters measured include carbon, neutralisation number, closed flash point temperature, open flash point temperature, kinematic viscosity, water content, ferrous wear debris, and the presence of elements such as iron and silicon. The results of these tests are then used to determine which parameters are in or out of specification based on pre-determined values. Understanding these parameters, and how they change over time, as illustrated for an organic fluid in **Table 3**, is crucial for understanding fluid degradation and maintaining its long-term health.

Table 3. Typical parameters for an organic-based heat transfer fluid with a maximum bulk and film temperature of 320 ℃ (606 °F) and 340 ℃ (644 °F), respectively.

Parameter	**Test**	**Typical values**
Density at 25 °C (77 °F), kg/m^3	ASTM D4052	873.0
Kinematic viscosity at 40 °C (104 °F), mm^2/s	ASTM D445	29.8
Kinematic viscosity at 100 °C (212 °F), mm^2/s	ASTM D445	4.5
Closed flash point temperature PMC, °C (°F)	ASTM D93	210.0 (410.0)
Open flash point temperature COC, °C (°F)	ASTM D92	230.0 (446.0)
Autoignition temperature, °C (°F)	ASTM E659	360.0 (680.0)
Pour point, °C (°F)	ISO 3016	−12.0 (10.4)
Neutralisation number (acid), mg KOH/g	ASTM D974	<0.05
Moisture content, PPM	ASTM D6304	<100.0

Values taken from [12].

5. Extending the lifespan of a fluid

As a fluid undergoes thermal cracking, carbon levels will increase and flash point temperatures will decline. Similarly, when a fluid is oxidised in the presence of oxygen, carbon levels will increase, and total acid number, an indicator of oxidative state, will also increase [41].

The accumulation of light-end hydrocarbons, flammable liquids, can progressively lower the flash point temperature of the HTF and, if not managed and removed regularly, this can increase the risk of plant fires [42]. Hence it is important to implement a regular fluid monitoring program, such as routine sampling of the fluid, and utilise available technologies, such as the installation of a light-ends removal kit [37], to accurately measure key fluid parameters and mitigate potential safety hazards.

5.1. Strategies for extending the lifespan of a fluid

Given that fluid degradation is inevitable and impacts component lifespan [1], an important approach to extending the system's lifespan is to limit degradation [43]. There are a wide variety of interventions and strategies to achieve this. These include:

- Routine and regular sampling: Improved fluid condition has been associated with sustained component life [34].
- Closely monitoring the markers of thermal degradation: Research has shown that carbon residue levels in organic fluids can serve as an early and sensitive marker for determining the overall condition of the HTF [44].
- Decreasing the maximum operating temperature: According to Arrhenius's Law, the decomposition rate is halved for every 10 degree Celsius drop in temperature [1].
- Dilution of the fluid: Adding up to 50% of the total volume with virgin HTF, works to remove degradation by-products from the system.
- Filtering the fluid: This process removes degradation by-products and helps avoid their potential catalytic effect on further fluid degradation [6].
- Removal of short-chain hydrocarbons ('light-ends') through distillation: This can be achieved by installing using either a temporary or permanent installation (see section below) [37].
- Choosing a good quality, high purity HTF.
- Recharging the system with a synthetic HTF instead of an organic HTF: This helps to maximise the operating temperature and improves thermal and oxidative stability [44].
- Mitigate the effects of oxidation at temperatures above 60 ℃: A nitrogen blanket in the expansion tank can help to reduce the formation of acids, which can lead to corrosion and the fouling of pumps and system components.
- Additive packages: These can be added to mitigate the effects of oxidation [6].

5.2. The role of a light-ends removal kit (LERK) in extending lifespan

The installation of a LERK system has been proven effective in managing short-chain hydrocarbons ('light-ends') and improving overall plant safety [42]. Following installation, critical fluid properties such as open flash point temperature, closed flash point temperature, and fire point temperature have been shown to stabilised for up to 11 years [45] and remain at levels close to those expected for a typical fluid (please see **Table 2**). A recent analysis of this data (unpublished) shows these parameters remaining stable for up to 14 years (**Figure 4**). In addition, values for carbon residue (≤0.35% weight) and total acid number (≤0.22 mg KOH/g) also remained stable throughout the follow-up period. These data highlight the effectiveness of the LERK and its ability, in combination with routine sampling, to effectively manage the lifespan of an HTF.

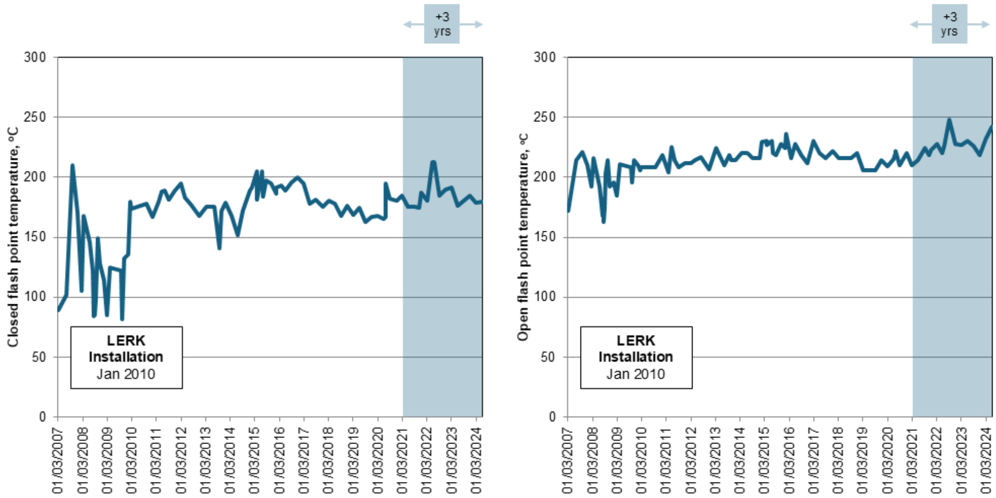

Figure 4. Case study showing the long-term stabilisation of closed and open flash point temperatures for up to 14 years after the installation of a light-ends removal kit.

6. Conclusions

The short review article introduces the types of HTFs utilised in industrial applications and their relative advantages and disadvantages (see **Table 4**). HTFs play a crucial role in various industrial processes, particularly in sectors such as concentrated solar power systems where they are used for power generation and energy storage. HTFs exhibit considerable variation, emphasising the importance of understanding a HTFs functionality, safety, and performance characteristics. The selection of an appropriate HTF is crucial, requiring careful consideration of factors such as cost-effectiveness, thermal stability, compatibility, and operating temperatures. Regular sampling and analysis of a fluid is essential to prevent / slow degradation and maintain optimal operational performance. Various strategies can be employed to maintain optimal conditions, such as the use of additive packages to resist oxidation and prolong the lifespan of the HTF.

Table 4. Brief overview of the different types of heat transfer fluids utilised in industrial applications.

Type of heat transfer fluid	**Temperature range**	**Advantages**	**Disadvantages**
Molten salt	Medium-to-high	High specific heat capacity, excellent thermal storage, non-flammable, safe, low-pressure, non-toxic	High melting point, but susceptible to degradation at elevated temperatures
Liquid metal	Medium-to-high	Exhibits excellent thermal conductivity and a wide liquid range, encompassing both low melting and high boiling points	Some metals are costly, reactive, corrosive, and potentially hazardous
Synthetic fluid	Medium-to-high	Characterized by a high initial boiling point, a narrow distillation range, enhanced stability, higher thermal conductivity, lower viscosity, and higher enthalpy than conventional organic HTFs	Higher fluid cost than organic fluids, longer service life than organic HTFs, higher freeze pour point than organic HTFs, easy to leaks, flammable/fire risk

Table 4. (*Continued*).

Type of heat transfer fluid	Temperature range	Advantages	Disadvantages
Organic fluid	Medium-to-high	Relatively lower cost than synthetic HTFs, good fluidity across temperatures, low freezing point, good heat transfer performance, low corrosiveness, relatively safe if routinely managed and maintained	High cost, relatively shorter service life, flammable/fire risk, easy to leak, in some more extreme lower temperature conditions viscosity can be weaken and lead to, for example, pipeline blockages and deterioration of the HTF, explosion/fire hazard
Water/steam	Low-to-medium	Low cost, non-toxic, low corrosiveness, low environmental impact in the event of leaks	High temperature requirements, high pressure requirements, low heat storage capabilities with water/steam

Conflict of interest: The author declares no conflict of interest.

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